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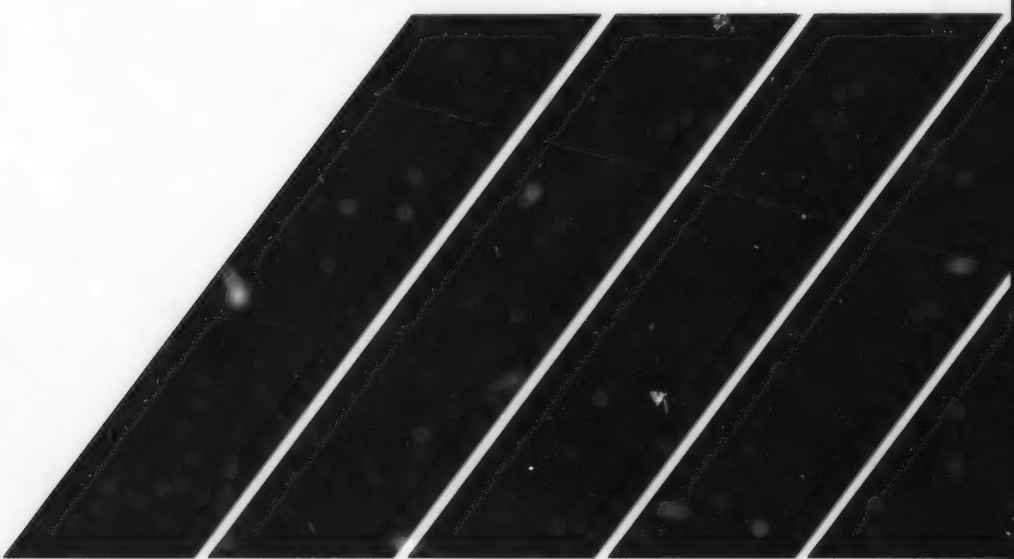

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DEVELOPMENT OF A PROGRAMMABLE LOGIC CONTROLLER FOR PHOTOVOLTAIC SYSTEMS

PREPARED FOR:

Efficiency and Alternative Energy Technology Branch
Energy, Mines and Resources Canada
DSS File No. 23440-0-9460
Ottawa, Ont.
September, 1991

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MICROMEDIA

24 pp

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EXECUTIVE SUMMARY

The purpose of this project was to demonstrate that a Programmable Logic Controller (PLC) could be used to control any PV system.

To date a typical PV system uses control components that are used by other electrical systems. This means that each PV system must be specifically designed for the application, and once designed, additions or changes are very difficult.

This project not only demonstrates that a PLC can be used to control a PV system, but that future changes can be accommodated easily, and that any other PV system can use many of the program building blocks developed under this project.

Most PV systems are used to supply electrical energy in locations not served by mains power. This was not the case for this project. In this case the system was installed on a private workshop. The system is used to supply all of the area lighting for the workshop as well as walkway lighting leading to the house. The system therefore is similar to an actual system in that the load on the system consists of both sporadic and consistent loads. As with typical systems an automatic backup electrical source has been provided. While this system is not installed in a remote location it does have all of the features of a typical system.

This system has been installed and operating for the past 6 months and has operated as expected. The only two components of the system that have not been fully field tested is the temperature compensation routine and the initiation of the standby battery charger. Since installation, the ambient daytime temperature has varied between 5C and 25C. This is not a sufficient swing to obtain definitive temperature compensation results. Similarly, since installation, as a result of the load shedding feature of the non critical load (path lights) the batteries have not reached a sufficient depth of discharge so as to cause the battery charger to be energized.

This project has demonstrated that a PLC is can be used to control a PLC system. By using a PLC as a controller, the component count has been reduced, it is compatible with any

PV system application, the control strategy can be changed at any time, the PV array size can be altered with no change in control component and for very remote locations the system can be programmed, and monitored via a land or radio link.

Appendices included with this report contain pictures, schematics, some monitored data, instruction code listings, application data request sheets, and a proposed controller for a typical PV system.

RÉSUMÉ

Le but de ce projet était de démontrer qu'un contrôleur logique programmable (CLP) pourrait être utilisé pour contrôler tout système PV.

Jusqu'à ce jour, tout système PV type utilisait des composantes de contrôle d'autres systèmes électriques. Cela signifie que chaque système PV doit être spécialement conçu pour l'application voulue et qu'une fois construit, il est très difficile de l'améliorer ou de le modifier.

Le présent projet vise à démontrer qu'un CLP peut non seulement servir à contrôler un système PV, mais peut aussi être modifié facilement, et que tout autre système PV peut utiliser un grand nombre des blocs de construction de programme élaborés dans le cadre du projet.

La plupart des systèmes PV servent à alimenter en électricité des endroits non servis par un réseau électrique. Cela n'a pas été le cas dans le présent projet. Le système a plutôt été installé dans un atelier privé. Il sert à alimenter tous les appareils d'éclairage de l'atelier ainsi que ceux de l'allée menant à la maison. Il ressemble donc à un vrai système du fait que la charge se répartit en charges tant sporadiques que constantes. Comme dans les systèmes types, une source électrique d'appoint automatique a été prévue. Même si ce système n'a pas été installé dans un endroit éloigné, il possède toutes les caractéristiques d'un système type.

Ce système a été installé et est exploité depuis six mois, et il fonctionne comme prévu. Les deux seules composantes qui n'ont pas été complétement éprouvées sur le terrain est le sous-programme de compensation de la température et la mise en marche du chargeur de batterie de secours. Depuis l'installation, la température diurne ambiante a varié entre cinq et 25 °C. Cette amplitude n'est pas suffisante pour produire des résultats de compensation de la température définitifs. De même, depuis installation, à cause de la caractéristique de délestage de la charge non critique (éclairage de l'allée), les batteries ne se sont pas assez déchargées pour déclencher la mise en marche du chargeur.

Ce projet a permis de démontrer qu'un CLP peut servir à contrôler un système CLP. En utilisant un CLP comme contrôleur, le nombre de composantes peut être réduit, il est compatible avec toute application de système PV, la stratégie de contrôle peut être modifiée en tout temps, la taille du panneau PV peut être modifiée sans toucher aux composantes du contrôleur et, dans les régions

très éloignées, le système peut être programmé et surveillé par une liaison terrestre ou radio.

Les annexes contenues dans ce rapport renferment des images, des schémas, quelques données de surveillance, des listes de codes d'instructions, des feuilles de demande de données sur les applications et une proposition de contrôleur pour un système PV type.

CITATION

Dirk and Price Engineering Ltd. *Development of a Programmable Logic Controller for Photovoltaic Systems*. DSS Contract No. 23440-0-9460. Efficiency and Alternative Energy Technology Branch, Energy, Mines and Resources Canada, Ottawa, Ontario. 1991 (24 pp.)

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NOTE

Funding for this project was provided by the Federal Panel on Energy Research and Development, Energy, Mines and Resources Canada.

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Catalogue No. M91-7/168-1992E
ISBN. 0-662-19374-1

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EQUIPMENT SPECIFICATIONS

PLC PROGRAMS

MONITORING

PROPOSED PV CONTROLLER

1. INTRODUCTION

Most PV systems currently are a collection of "off the shelf components". A typical larger PV system would have a voltage regulator, a low voltage disconnect, system status lamps, transfer switch controls, load shedding controls etc.

A PLC can be used to replace all of these separate control components thus simplifying the installation and reducing the overall cost. The system will also have expansion capabilities and can accommodate future changes or upgrades.

The PV system described by this paper while not large, does contain all the components of a large standalone system. As designed and installed the PLC is used to perform all of the required control functions for this system. If the PLC were not used as a controller approximately 10 individual and separate control components plus a bank of status lights would be required to perform the same control functions.

2. A PROGRAMMABLE LOGIC CONTROLLER (PLC)

A PLC is an industrial computer used for the control of any manufacturing and process equipment. The PLC was introduced to the auto industry in the early 1970's as a replacement for relay racks used to control the assembly lines. At that time the main feature was its ability to make control changes without having to make physical wiring changes. When a new car model was to be assembled, rather than replacing the relay control logic the PLC was simply reprogrammed. Turn around time became hours instead of weeks.

A PLC consists of a microprocessor controlled set of input and output terminals. The system controlling elements (contacts and analogues) are connected to the input terminals and the controlled elements (lights, transfer switches, array switches) are connected to the output terminals. The program instructions are stored in the computer memory, accessed by the microprocessor and then cause the system to operate as per the program. The programming language is Ladder Logic or Boolean Statements. This is a language that is familiar to all electricians. This language is used because the first PLC's were used to

replace relay panels and ladder logic is used to specify relay sequences. PLC's today, however, have been developed to the point where they are capable of very sophisticated statements including mathematical manipulations and conditional statements. This makes the unit very versatile and powerful as it can be used for very simple systems or for the complete process control of a large plant.

PLC's are expandable and the program can be changed on site by using either a hand held programmer or an MS-DOS operated computer. A hard copy of the program is available by connecting the PLC to a conventional printer. Once the program is installed into a PLC it remains there, even if the supply voltage fails.

3. PV SYSTEM CONTROL REQUIREMENTS

Prior to the selection of a PLC for this project, several PV system suppliers were contacted in an effort to determine the range and type of controls that were required for PV systems. This information was then assembled and put into block form as shown by Fig 1, page 3. From a programming point of view these blocks represent the program segments that are required. A segmented program is also convenient because each system will use some of the blocks but not others. When a controller is designed for a particular application the designer need only select the required blocks.

4 A PLC CONTROLLED PV SYSTEM

Fig 2, page 4 shows a single line diagram of a typical PV system as it would be controlled by a PLC. The PLC inputs and outputs that are shown on this single line diagram are typical of those that would be required. When using a PLC as a controller, a designer has the option of specifying the devices that are to be monitored and controlled. The actual control scheme is totally arbitrary. In general, the procedure is to arrange for numerous inputs and outputs and then as the design proceeds, determine how the various components are to be controlled. Since the actual control scheme is programmed via a keyboard the program can be inserted into the PLC at any time during the design process as well as during startup.

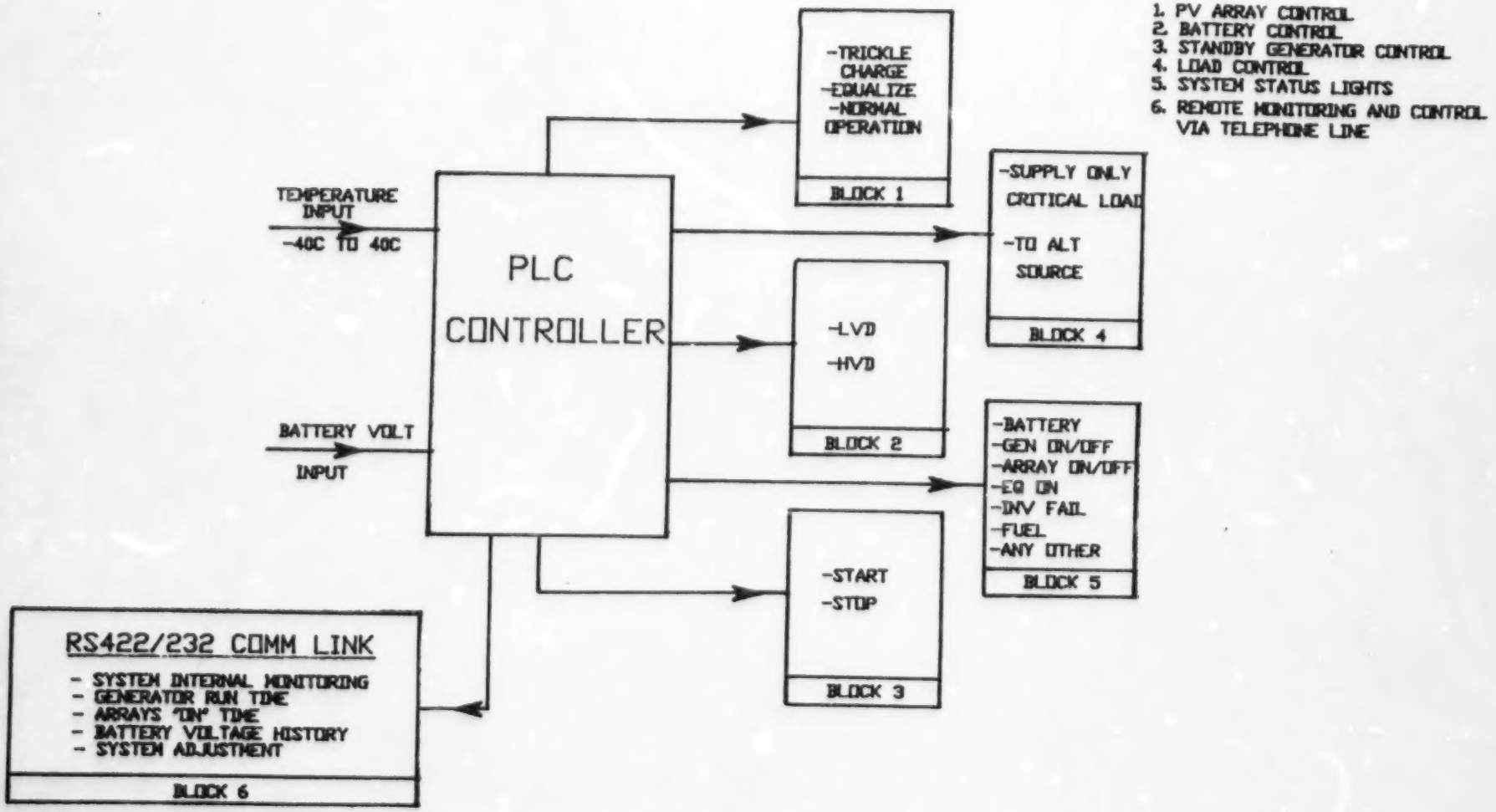
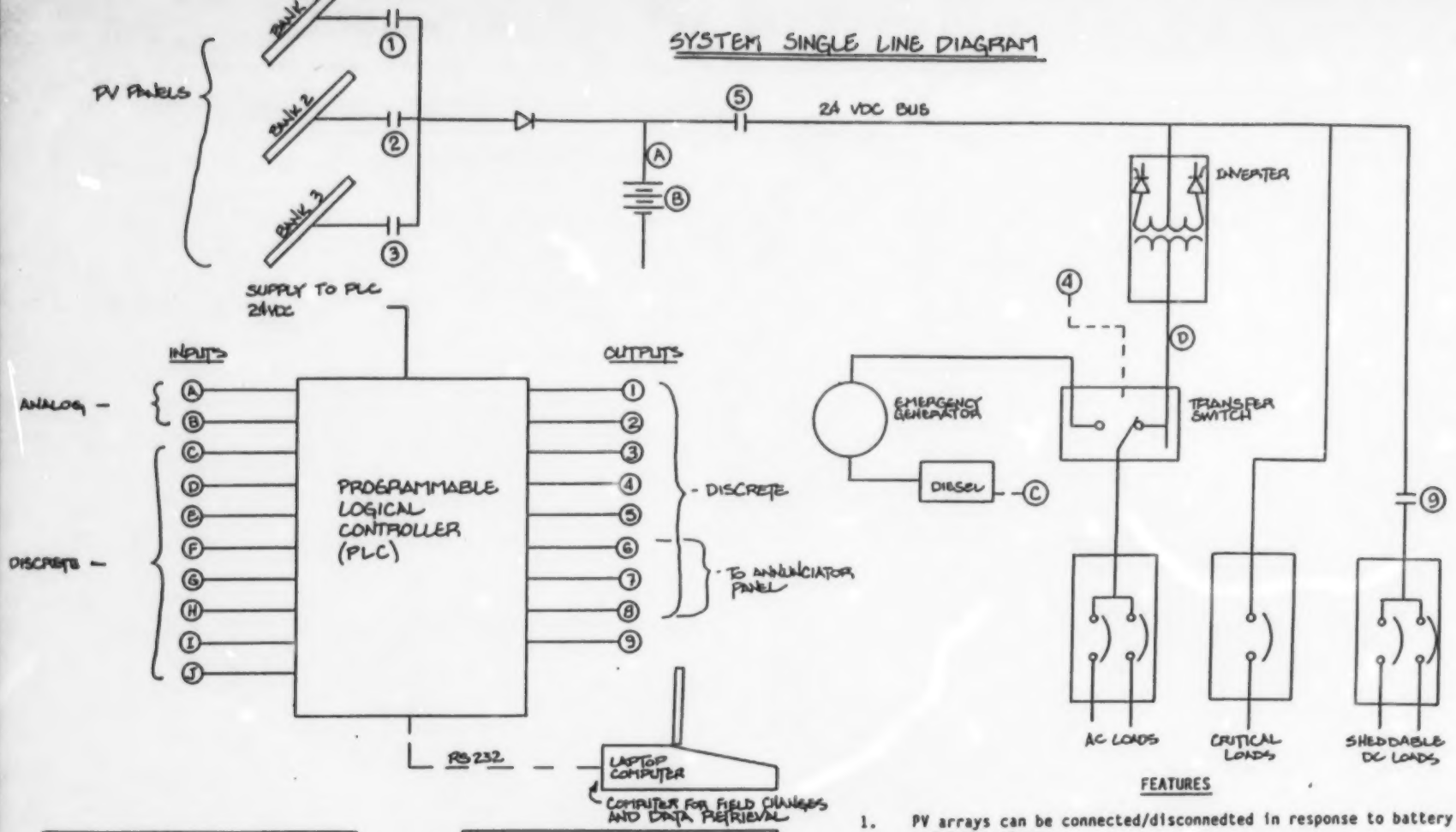


FIG 1

PROGRAM BLOCKS FOR A PLC CONTROLLED PV SYSTEM



INPUTS	
#	DESCRIPTION
A	BATTERY VOLTAGE
B	BATTERY TEMPERATURE
C	DIESEL LEVEL
D	INVERTER FAILURE
E	SPARE
F	
G	
H	
I	
J	

OUTPUTS	
#	DESCRIPTION
1	BANK #1 CONTROL
2	BANK #2 CONTROL
3	BANK #3 CONTROL
4	GEN START/STOP / LOAD TRANSFER
5	LOAD DISCONNECT
6	BATTERY VOLTAGE O.K.
7	BATTERY LOW VOLTAGE ALARM
8	LOW DIESEL ALARM
9	LOAD SHEDDING

FIG 2.

PLC Controlled PV System

FEATURES

1. PV arrays can be connected/disconnedted in response to battery SOC and temperature.
2. Arrays connect/disconnect set points are temperture compensated @ n/mv/deg where n is programmable.
3. DC and AC load shedding in response to battery SOC.
4. Annunciator lamps can be programmed at will.
5. Typical information stored in PLC and accessible:
   i) number generator starts;
   ii) generator run time;
   iii) arrays connect time
6. Programmable on site.
7. Information data transfer via telephone line.
8. Number of inputs and outputs is expandable.

In this schematic 10 inputs and 9 outputs are shown. PLC's are expandable, thus allowing for increasing the number of inputs and/or outputs as required.

5. THE SYSTEM AS INSTALLED

As indicated previously the purpose of the project was to demonstrate the use of a PLC as a controller for any PV system. It has been our experience that if a system is set up and the load is simulated, then some real life consequences are missed during the project. Since in this case the PV system is not the primary source of electrical energy, it was decided to use the system to supply various loads for a residential property rather than attempt to simulate a load. Installation photographs are shown in Appendix 1

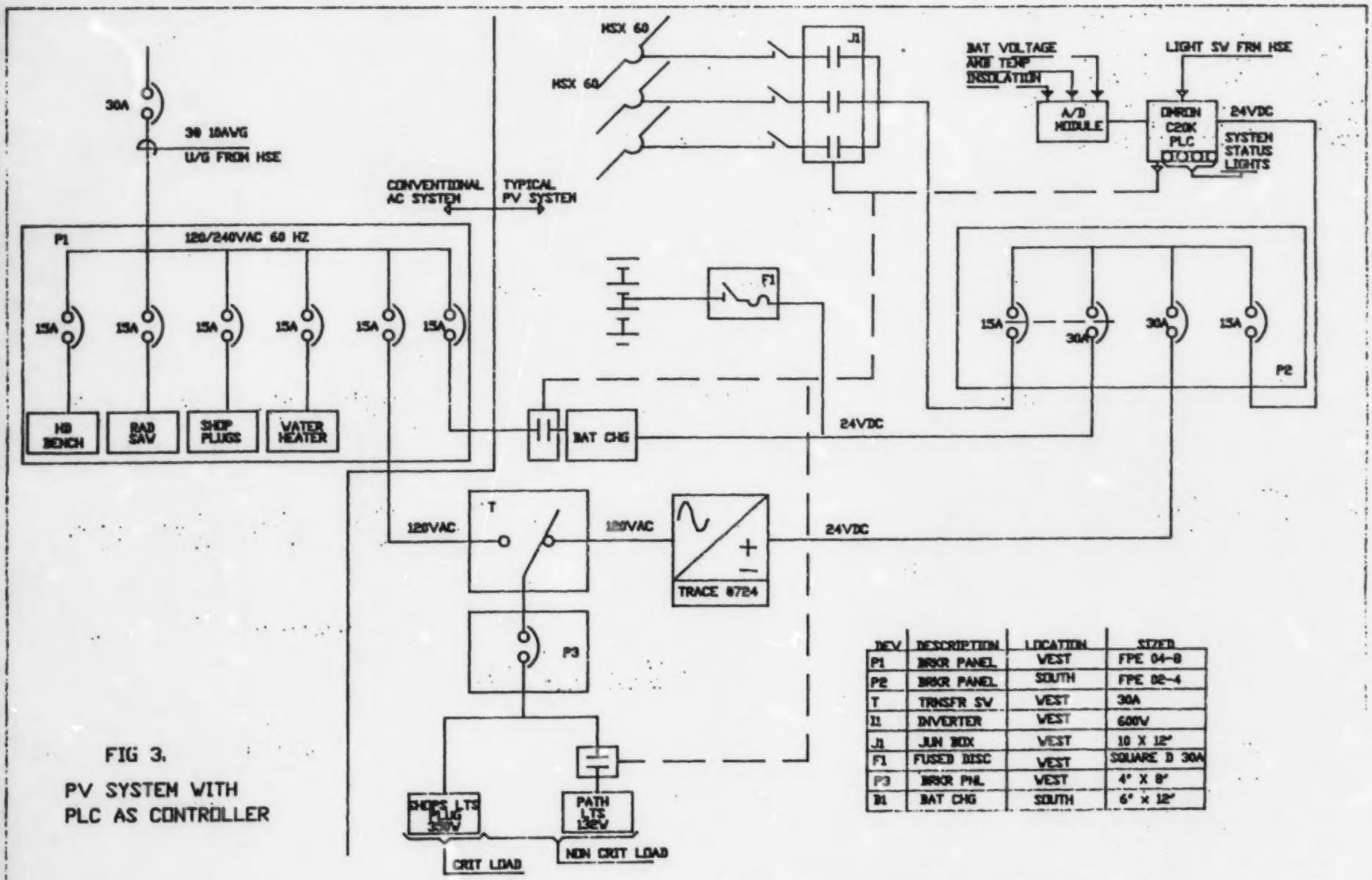
A schematic of the system as installed is shown by Fig 3. This system has been installed in a shop that is used by the owner of the residence. As is shown by the drawing, the entire system consists of a conventional AC system interconnected to a PV system through a transfer switch.

The load on the PV system consists of shop and path lights. The path lights are deemed to be not critical (can be disconnected if required), while the shop lights must be available at all times. In the event of a totally discharged battery, the PLC will connect the battery charger to the conventional AC system, thereby providing sufficient charge for the shop lights. A transfer switch has been installed to insure that shop lights are available in the event of a catastrophic PV system failure.

5.1 THE PLC

Several different PLC's were considered for this project. Any of those investigated would have performed the required control functions, however the two main criteria, cost and standby current resulted in the selection of an OMRON C20K PLC for the this project.

This PLC has 12 discreet input and 8 discreet output points as well as 4 analogue input points. It can be programmed by using a DOS operated computer or by the use of a hand held



DEV	DESCRIPTION	LOCATION	SIZED
P1	BRKR PANEL	WEST	FPE 04-8
P2	BRKR PANEL	SOUTH	FPE 02-4
T	TRNSFR SV	WEST	30A
I1	INVERTER	WEST	600V
J1	JUN BOX	WEST	10 X 12"
F1	FUSED DISC	WEST	SQUARE D 30A
P3	BRKR PNL	WEST	4" X 8"
B1	BAT CHG	SOUTH	6" x 12"

FIG 3.

PV SYSTEM WITH PLC AS CONTROLLER

programmer. Once entered, the program is maintained by a lithium battery having a life of 5 years. The C20K has 4 self diagnostics of which one is low internal battery. When connected to a telephone line through a communication module, remote data retrieval and changes can be made. The PLC complete with the analogue module attached is 100mmX100mmX150mm.

5.2 PV ARRAY CONTROL

The PV array used for this project consists of three groups of 2 PV panels in series. Each PV group is controlled by a relay that is connected to a PLC output point. This allows individual bank control. Several charge control schemes were tested. The current scheme, which seems to be best suited for this application, has the PV banks staged such that as the battery SOC increases the 3 PV arrays are disconnected and reconnected at 3 different voltage values each having an ON/OFF window of 0.5V. The characteristic of the battery is such that at a particular charging rate the battery terminal voltage may be 26.5 volts. If an array is disconnected the voltage will immediately drop to some new value, say 26.2V and then continue to drop to a final value of 26V. Because of the required narrow voltage control window, frequent relay cycling occurs near full SOC on sunny days. This is prevented by introducing a time delay on each stage such that the battery voltage must remain at or above a set point value for 15 minutes prior to array switching. This allows the battery to charge to a slightly higher value than is required for array switch off, and consequently after switch off settles to a value slightly above the reconnect set point for that bank.

Observation has shown that for this system, as the SOC increases, stage 1 and 2 are disconnected and stage 3 remains connected to the battery thus maintaining a trickle charge to the battery.

5.3 LOW BATTERY VOLTAGE CONTROL

A portion of the load supplied by the PV system has been designated as critical. This means that its source must be secure. A subroutine has been included to monitor the SOC and in the event the minimum set point is reached, the battery charger is energized battery charger is energ charged. A time delay has been included in this module to prevent momentary battery voltage dips from energizing the battery charger.

5.4 PLC INPUTS

As is shown by Fig 3, the PLC has analogue inputs. The battery voltage is used for PV array charge control. The temperature input is used to modify the SOC voltage set points in response to changing battery temperatures. The third input, a single PV cell, is used to obtain current ambient light levels (see section 5.5). All of these signals are processed through the analogue input module, scaled, and available in the memory as base 10 values between 0 and 256. For the system of Fig 3 the PLC has 11 inputs and 3 outputs not being used.

5.5 LOAD CONTROL

The residence where this PV system has been installed has path lights between the parking area and the house. These path lights have been programmed to be on for three hours each night starting at dusk. The path lights can also be actuated by a remote OFF/ON switch. A load shedding feature has also been incorporated into the program such that in the event of a low battery SOC (higher than that required for battery charger turn on) the path lights will respond to the remote switch only.

6 APPROVALS

One of the major difficulties for the PV industry has been the ability to have installations approved by the authorities having jurisdiction. The installation as shown by figure 4 was inspected by the local inspector and was approved with no exceptions.

7. FURTHER WORK

This project has demonstrated that a PLC can be used as a controller for PV systems. As a result of our conversations with various PV system suppliers it is obvious that there is a need for a flexible controller capable of performing a wide range of control functions for PV systems. The requirement is for an APPROVED fully integrated power and control center capable of performing all of the required system control, monitoring and distribution functions.

This need has resulted in preliminary negotiations with one of the major Canadian PV equipment suppliers for the manufacturer and supply of a control and distribution center similar to that shown in Appendix 5.

SYSMAC C20K...

- **20, 28 or 40 I/O on the CPU; expandable up to 84 I/O**
- **Reversible and high-speed drum mechanism for sequence control functions are standard**
- **Expansion modules available in 4, 16, 20, 28 and 40 I/O point units**
- **Optional module with 4 analog-set timers**
- **I/O link and host computer communications capabilities**
- **I/O refresh and user-selectable fixed scan time**
- **Provides 24 VDC power supply to inputs**

C20K family . . . newest C-series micro PCs

offers the most flexible I/O options

The most capable micro PC smart money can buy is Omron's C20K. It offers big machine functions in a compact unit designed for track or surface mounting. With the widest variety of expansion units available today, the C20K lets you configure just the system you need for the job.

The C20K family accepts AC and DC inputs with a choice of relay, transistor and triac outputs. The table below shows I/O designations.

A powerful, easy-to-use instruction set lets you perform four-function math in BCD in addition to ladder logic control. For program execution control, SYSMAC C20K gives you big machine features: jump function; immediate I/O refresh; programmable subroutines to perform specific functions when conditions are right; true sequence control; and the ability to set a fixed scan time to synchronize other equipment.

A high-speed drum mechanism with 2 kHz response frequency and reversible drum sequencing are provided in addition to 48 timers/counters. An optional timer module with four analog-set timers expands that capability. Each can be programmed for four ranges from 0.1 to 600 seconds. Extensive diagnostic relays let you monitor operations and initiate alarms or backup functions for troubleshooting.

The C20K offers host computer and I/O link networking capabilities with other C-series controllers and uses C-series peripherals.

SYSMAC C20K simplifies long-term maintenance. The self-contained CPU in the top portion of the unit prevents accidental damage during servicing. A PROM socket, located in the front panel, allows easy insertion and removal of chips. Inside, relays are socket-mounted for easy replacement and a relay pulling tool is supplied. Fuses are mounted in holders for easy removal and insertion. A detachable, snap-on terminal strip eliminates time-consuming field rewiring of I/O when C20K needs to be serviced or replaced.

Description	Inputs	Outputs
C20K CPU	12	8
C28K CPU	16	12
C40K CPU	24	16
20-point expansion	12	8
28-point expansion	16	12
40-point expansion	24	16
16-point expansion	16 inputs or 16 outputs	
4-point expansion	4 inputs or 4 outputs	

PLC PV CONTROL SYSTEM PROGRAM

STEP	INSTRUCTION		
0	LD 002		
1	CLC(41)		
2	LD 002		
3	SUB(31)		TEMPERATURE
	DATA A	#0171	
	DATA B	DM 00	
	DATA C	DM 01	COMPENSATION
4	LD 1813		
5	MUL(32)		
	DATA A	DM 01	
	DATA B	#0005	
	DATA C	DM 03	MODULE
6	LD 0002		
7	CLC(41)		
8	LD 1813		
9	ADD (30)		
	DATA A	9000	
	DATA B	DM03	
	DATA C	DM 05	
10	LD 1813		
11	DIV(33)		
	DATA A	DM 05	
	DATA B	#0100	
	DATA C	DM 06	
12	LD 1813		
13	MOV(21)		
	DATA A	DM 06	
	DATA B	DM 08	
14	LD 1813		
15	CMP(20)		
	DATA A	#0171	
	DATA B	DM 00	
16	LD 1904		
17	AND NOT	1907	
18	ADD(30)		
	DATA A	#100	
	DATA B	DM 06	
	DATA C	DM 08	
19	LD 1813		
20	OUT 0200		

PM 51

STEP	INSTRUCTION		
21	LD 1813		
22	OUT 0201		
23	LD 1813		
24	OUT 0202		
25	LD 1813		
26	OUT 0203		
27	LD 300		
28	OUT 1000		BATTERY
29	LD 301		
30	OUT 1001		VOLTAGE
31	LD 302		
32	OUT 1002		
33	LD 303		AND
34	OUT 1003		
35	LD 304		BATTERY
36	OUT 1004		
37	LD 305		TEMPERATURE
38	OUT 1005		
39	LD 306		INPUT
40	OUT 1006		
41	LD 307		MODULE
42	OUT 1007		
43	LD 308		
44	BCD(24)		
	DATA A	10	
	DATA B	DM 20	
45	OUT 204		
46	LD 309		
47	BCD(24)		
	DATA A	10	
	DATA B	DM 21	
48	OUT 205		
49	LD 310		
50	BCD(24)		
	DATA A	10	
	DATA B	DM 22	
51	OUT 206		

STEP	INSTRUCTION			
52	LD 311			
53	BCD(24)			
	DATA A	10		
	DATA B	DM 23		
54	OUT 207			
55	LD 1813			PV MODULE 1
56	COMP(20)			
	DATA A	DM 22		HI VOLTAGE
	DATA B	DM 19		
57	LD 1905			DISCONNECT
58	TIM 00			
	DATA A		50	
59	LD NOT 406			
60	LD TIM 00			
61	OR 105			
62	AND LD			
63	OUT 105			
64	LD 1813			
65	CMP(20)			
	DATA A	DM 22		
	DATA B	DM 18		
66	LD 1906			
67	OUT 400			

STEP	INSTRUCTION			
68	LD 1813			
69	CMP(20)			
	DATA A	DM 22		
	DATA B	DM 17		
70	LD NOT 401			
71	READ LD 1905			PV MODULE 2
72	OR 106			
73	AND LD			HI VOLTAGE
74	OUT 106			
75	LD 1813			DISCONNECT
76	CMP(20)			
	DATA A	DM 23		
	DATA B	DM 16		
77	LD 1906			
78	OUT 401			

STEP	INSTRUCTION			
79	LD 1813			
80	CMP(20)			
	DATA A	DM 22		PV MODULE 3
	DATA B	DM 15		
81	LD 1905			HI VOLTAGE
82	AND 1902			
83	LD NOT 1905			DISCONNECT
84	CNT 02			
	DATA A		900	
85	LD CNT		2	
86	OUT 107			

STEP	INSTRUCTION			
87	LD 1813			
88	COMP(20)			LOW VOLTAGE
	DATA A		20	
	DATA B		24	DISCONNECT
89	LD 1907			
90	AND 1902			

STEP	INSTRUCTION		
91	LD NOT 1907		
92	CNT(01)		
	DATA A	9000	
93	LD CNT 01		
94	AND NOT CNT 04		PATH LIGHTING
95	LD 03		
96	AND LD		TIMER
97	OUT 102		
98	LD CNT 01		AND
99	AND 1902		
100	LD NOT 1907		HOUSE SWITCH
101	CNT 04		
	DATA A	9999	
102	LD 002		TRIGGER CCT
103	AND 1902		
104	LD NOT 0002		
105	CNT 05		
	DATA A	9000	
106	LD NOT 0002		
107	AND 1902		
108	LD 0002		
109	CNT 06		
	DATA A	9000	
110	LD 0002		
111	AND NOT CNT 05		
112	LD NOT 0002		
113	AND NOT CNT 06		
114	OR LD		
115	OUT 100		
116	END(01)		

DATA INTERPRETATION

This appendix contains plots of battery data for the period April 17 to April 26 in 10 minute intervals as well as a Battery Vs Insolation voltage.

During the 10 days shown by this data, the PV system was connected as per the schematic shown on page 6. Path lights were programmed to come on each night at a time determined by the individual cell (see photographs Appendix 1), and the shop lights were used as required.

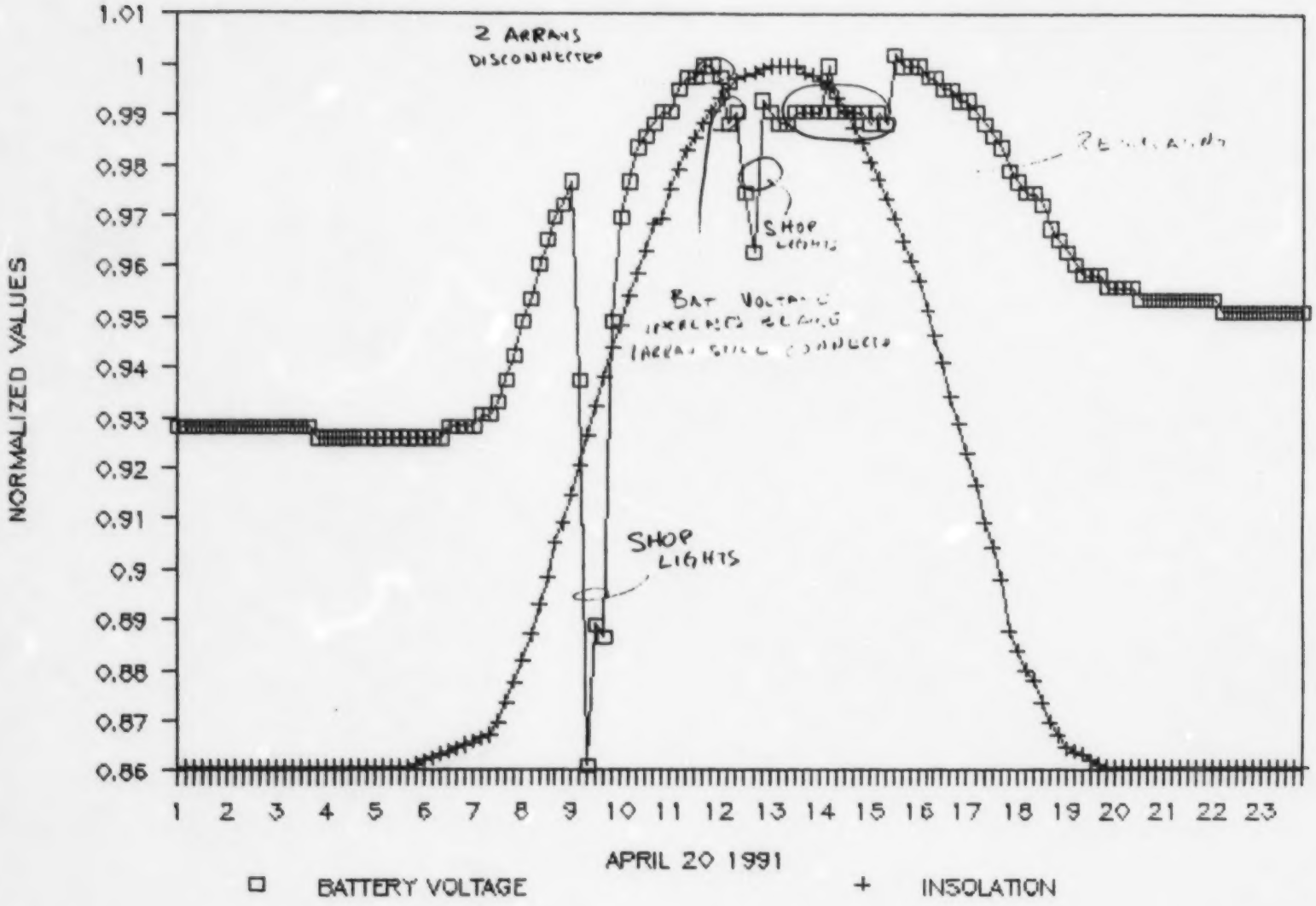
The effect of the path lights is clearly shown by the graph for April 22. The path lights came on at 6:45 and shut off approximately 3 hours later at 9:45.

Regulation is shown by the Battery Vs Insolation graph and the battery voltage curve for April 20, 1991. The insolation curve shows that it was sunny all day.

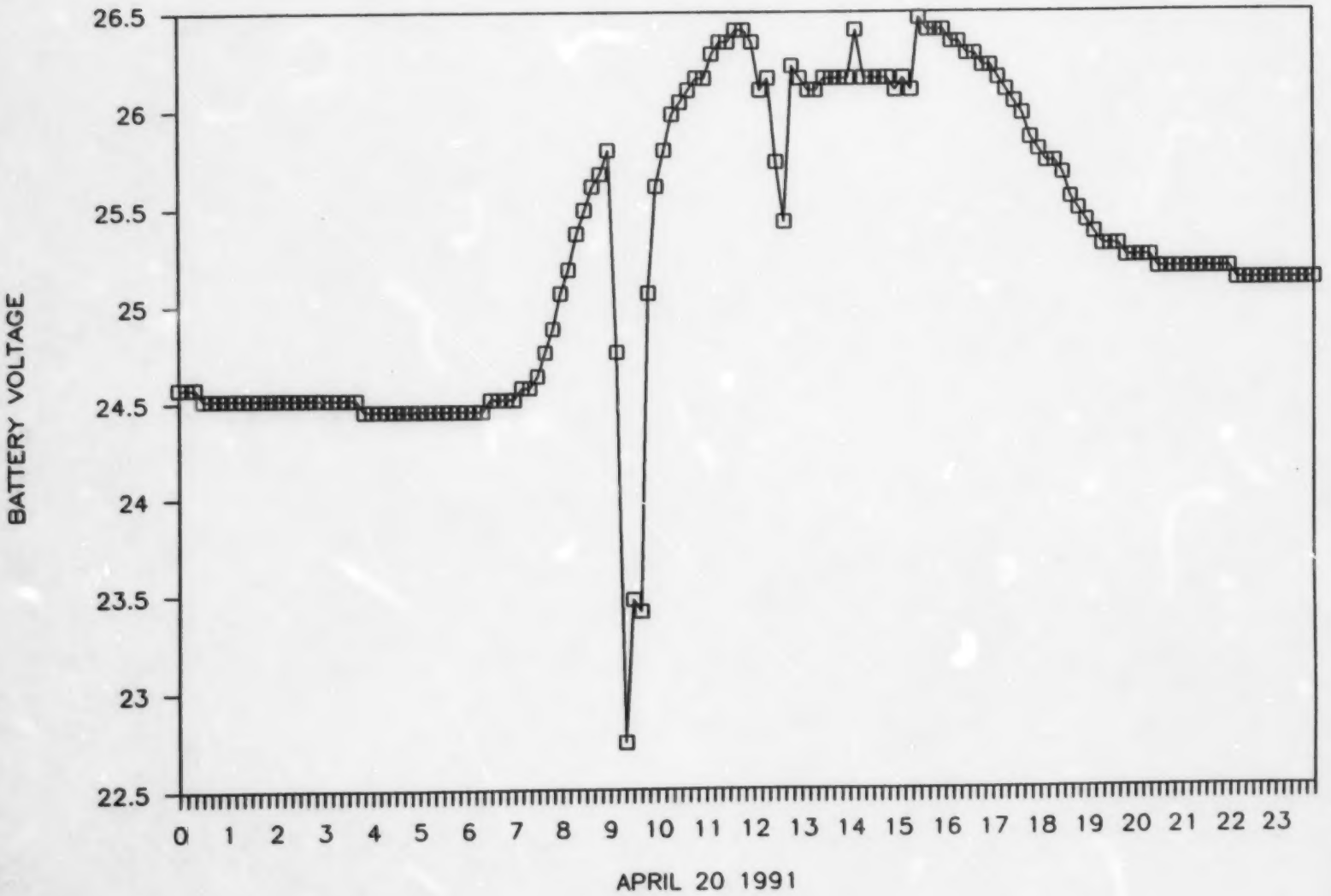
The following paragraph describes the action of the system during a typical day.

The battery voltage was constant at 24.5V until approximately 7AM. The sun caused the battery to charge resulting in the battery voltage increasing to approximately 25.8V. At 9AM a load was placed on the system (shop lights) and lasted until about 10AM. The battery then continued to charge until it reached the first set point of 26.4V. Two of the banks were disconnected, and the battery voltage dropped to an equilibrium value of 26.1V. Shop lights were turned on for 40 minutes, and the battery voltage dropped. When the battery voltage reached the lower set point, all of the panels are reconnected and the battery voltage increased momentarily because of the increased charging rate. The battery voltage continued to decrease until the load was disconnected. The battery voltage increased rapidly to the set point value, overshoots slightly and settles down to a constant value even though the sun is still bright. During regulation the panel relays are cycling (see 5.2 of the text) and since the sample rate is once every 10 minutes, a variation in battery voltage may or may not be detected. As the solar intensity decreases, all of the panels are reconnected to the battery, but the intensity is such that the charging rate does not increase the battery voltage to the top of the set point window. The battery voltage then follows the trailing insolation curve to an equilibrium at the end of the day approximately 0.7V higher than in the morning.

BATTERY VOLTAGE VS INSOLATION



PLC REGULATION CURVE



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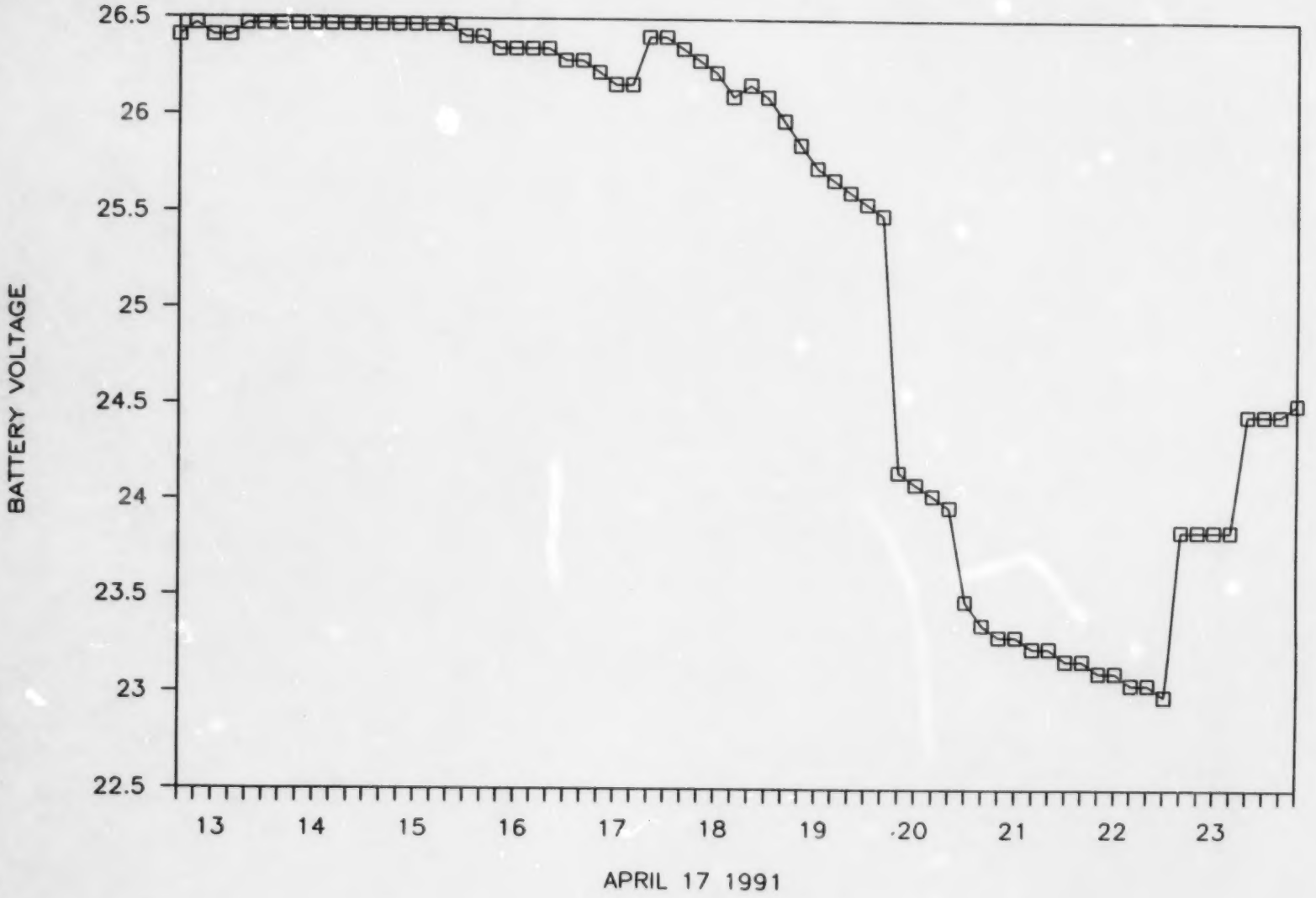

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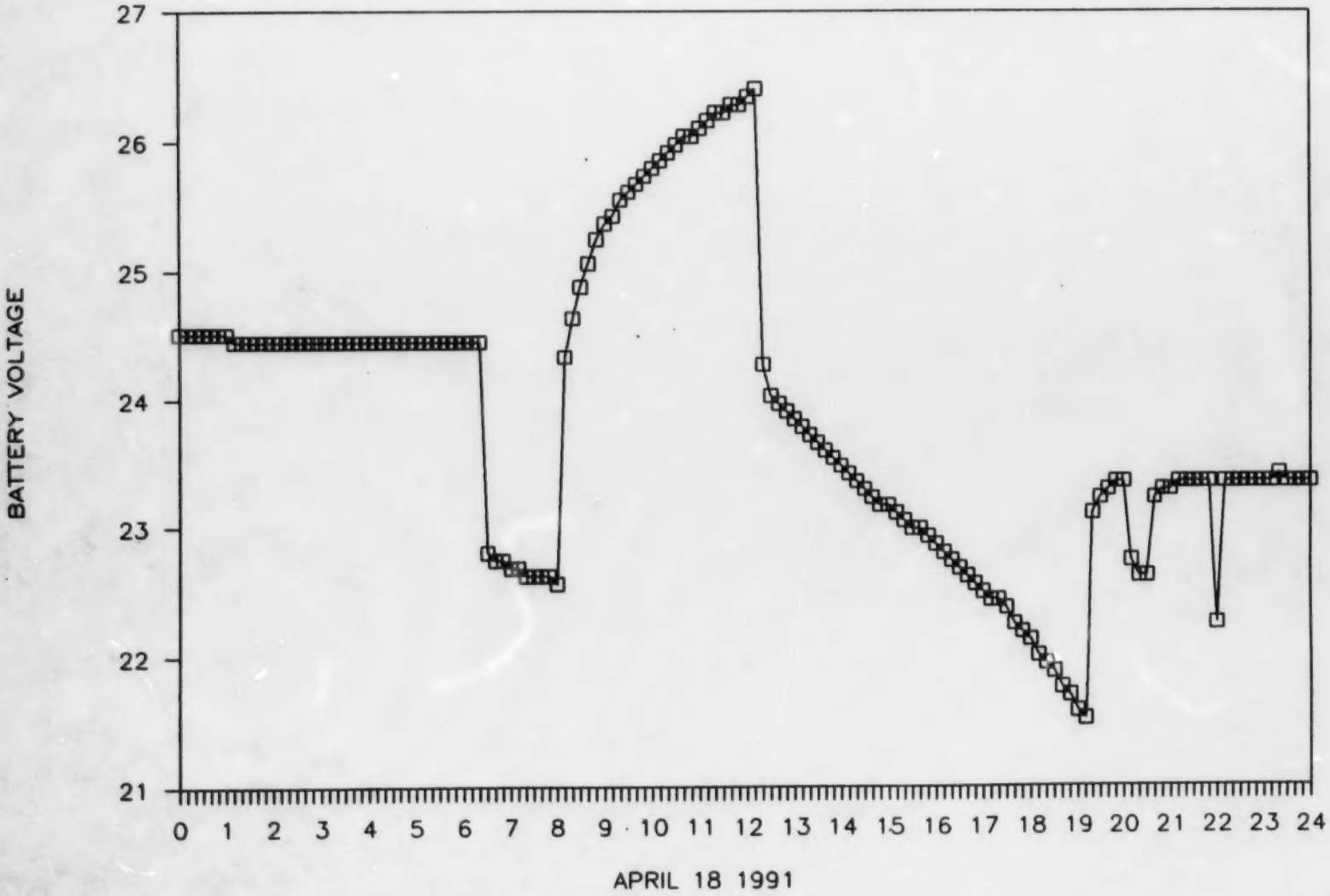

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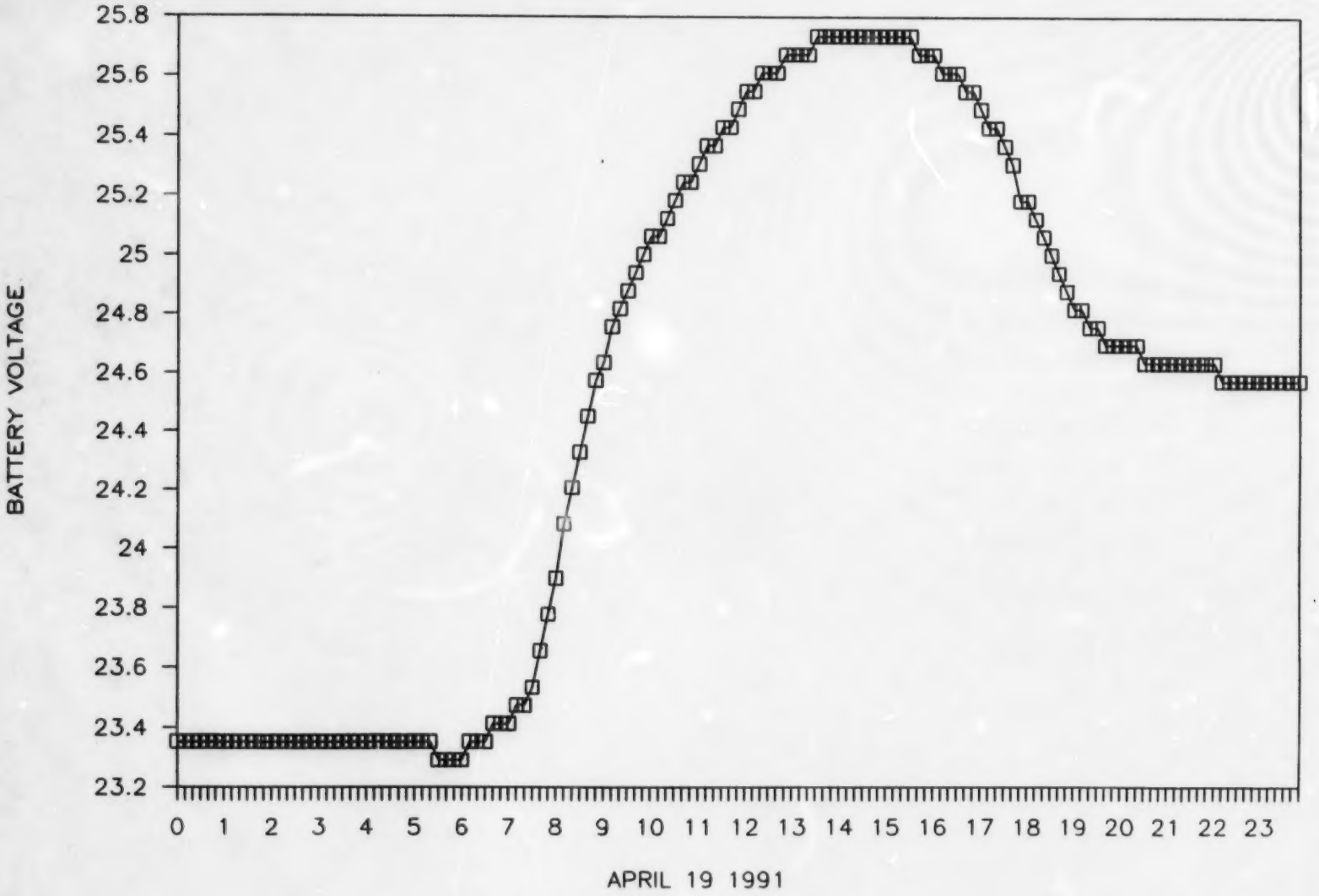

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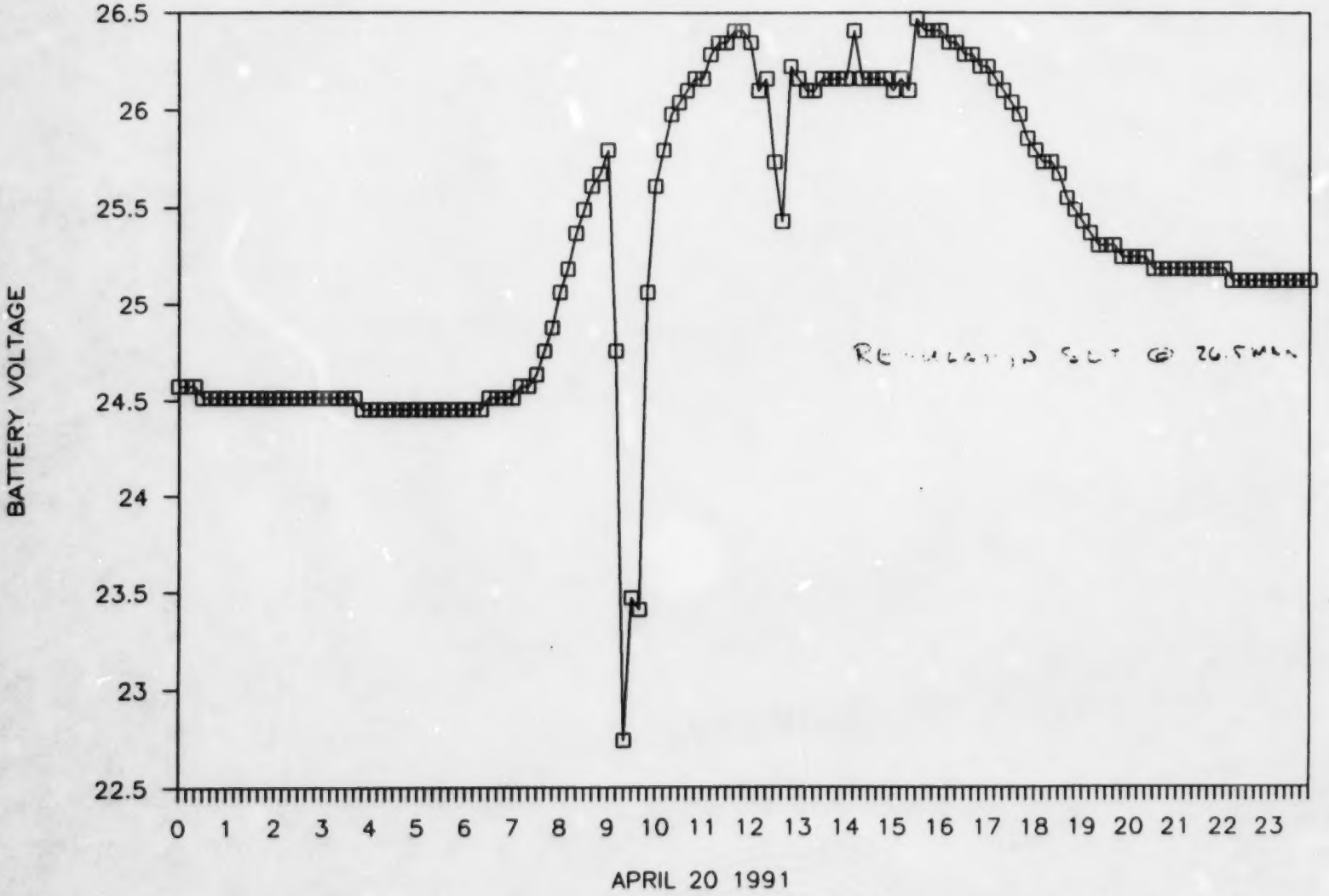

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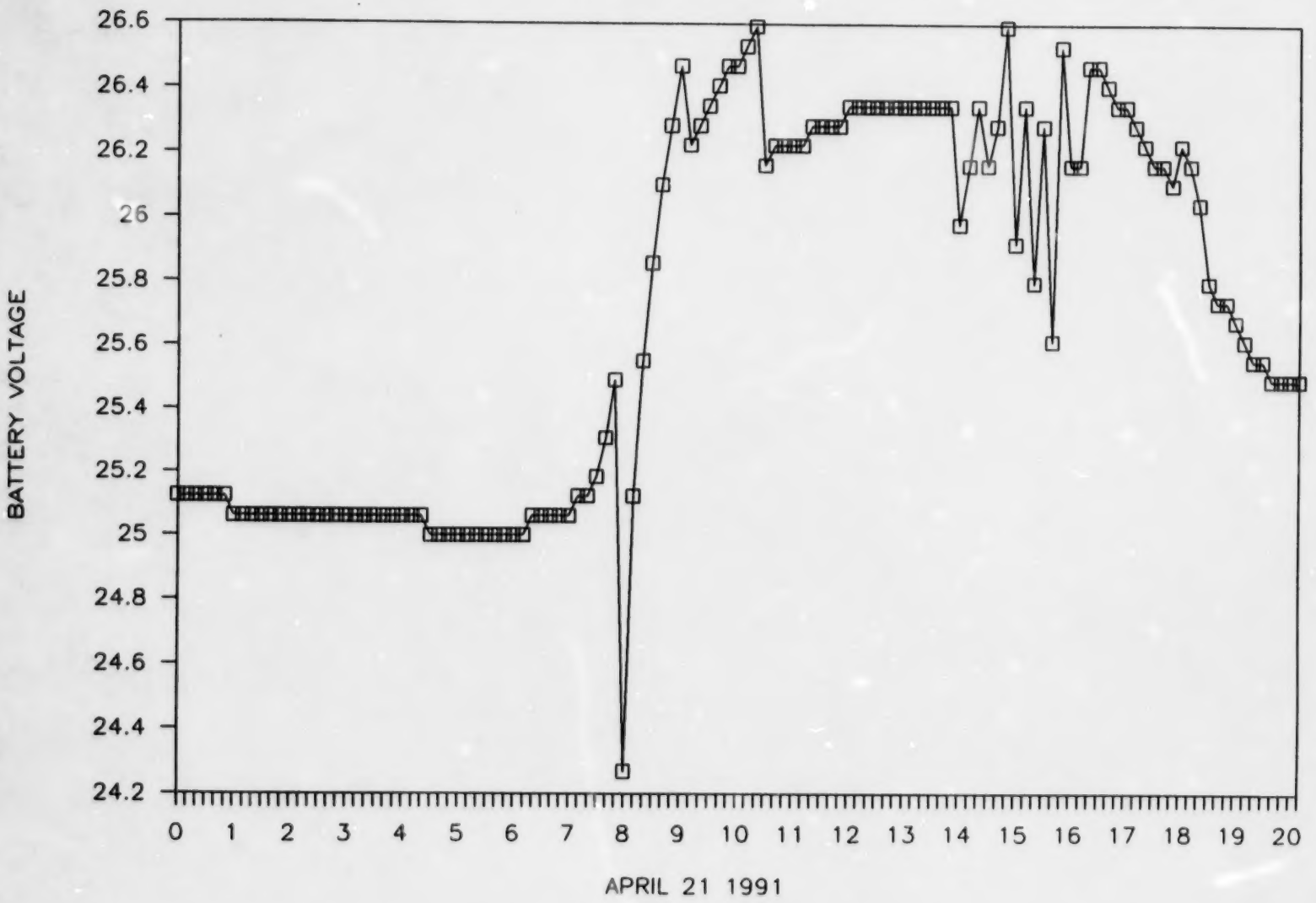

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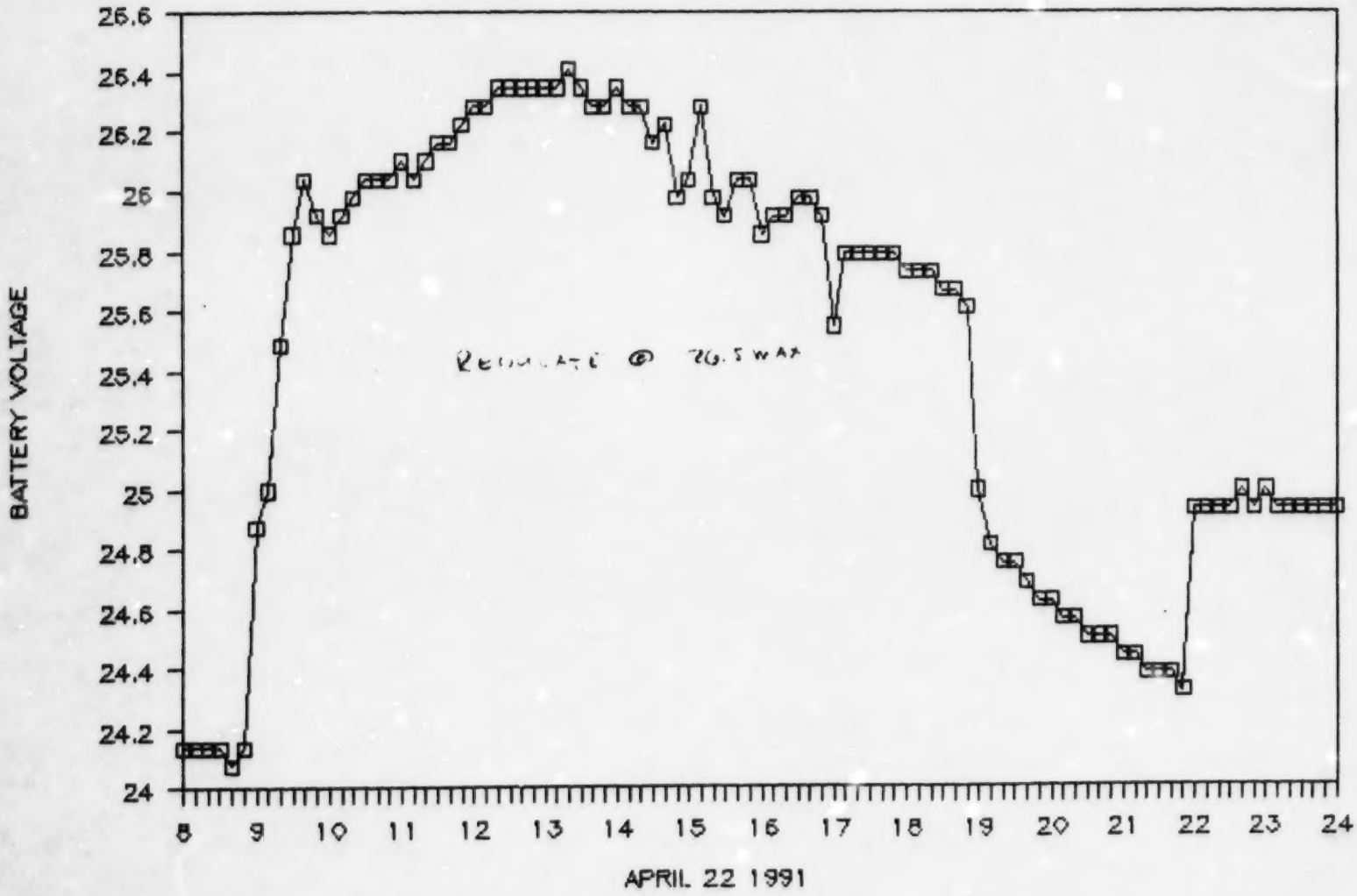

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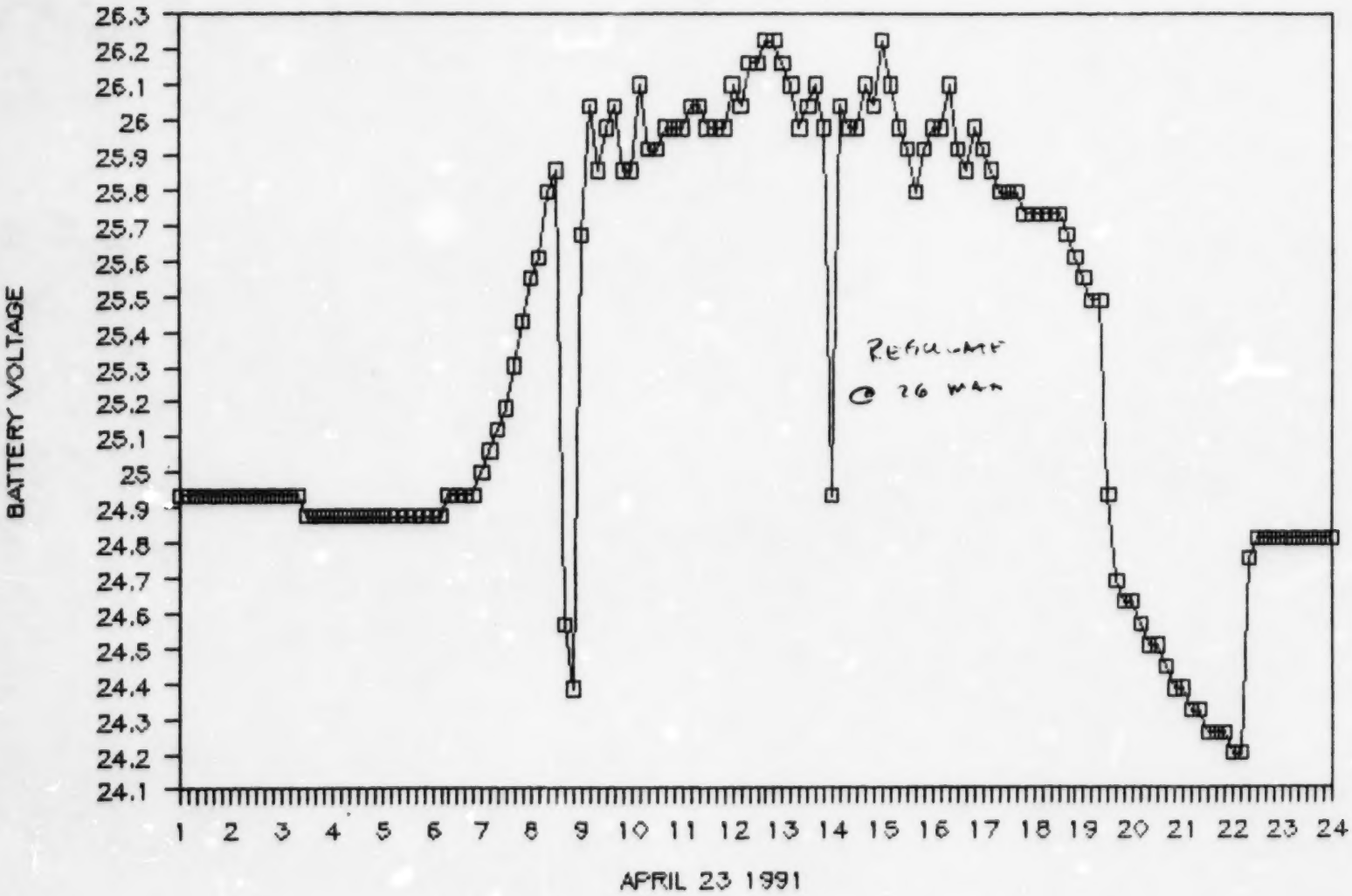

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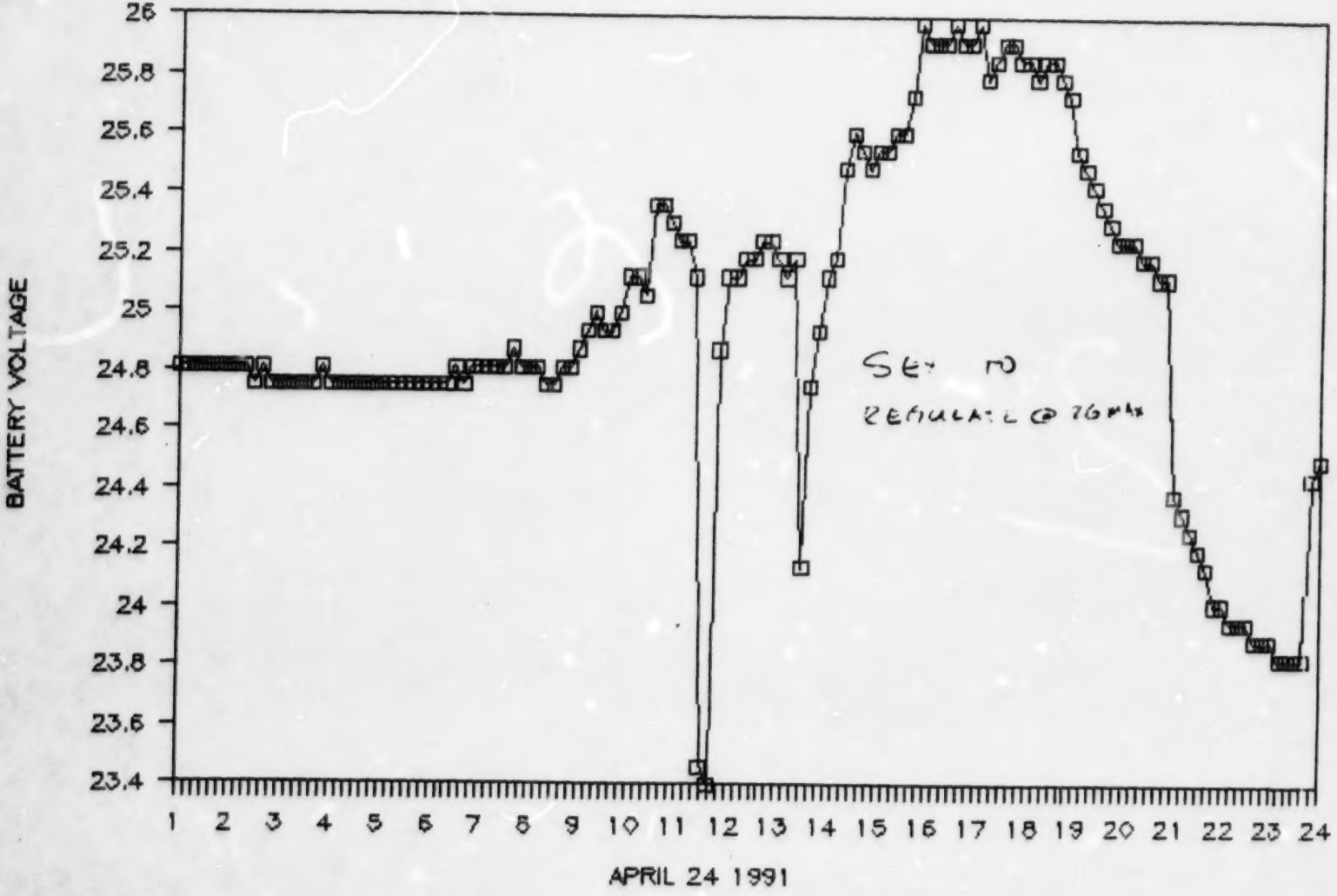

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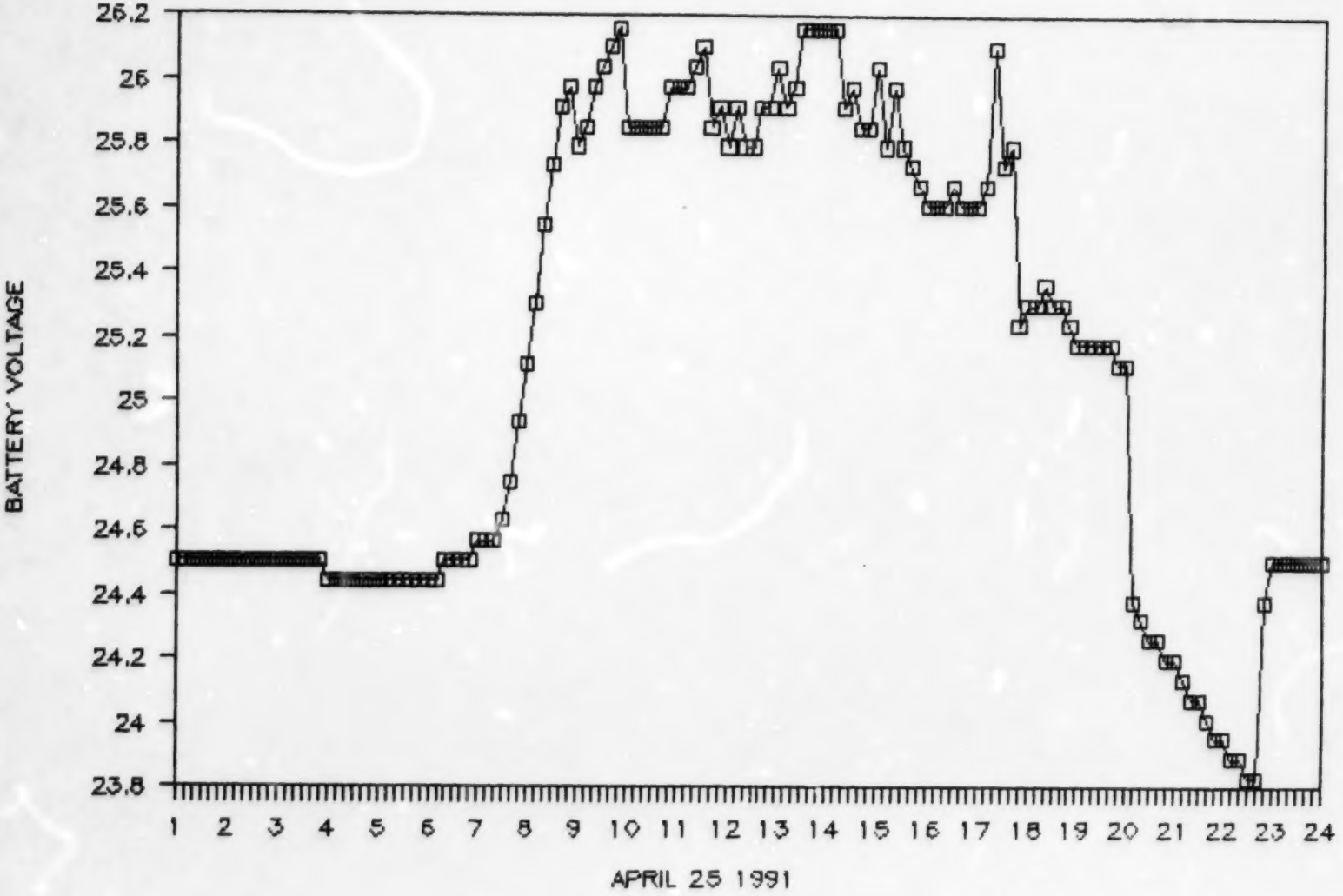

PLC REGULATION CURVE